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FINAL PROJECT REPORT
SUMMARY OF RESEARCH ACTIVITIES
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AT THE UNIVERSITY OF CHICAGO, 1993-95

NASA/GRO grant NAG 5-2081, at the University of Chicago, has provided support for a broad program of theoretical research in nuclear astrophysics and related areas, with regard to γ -ray and hard X-ray emission from classical nova explosions. This research emphasized the possible detection of ^{22}Na γ -ray line emission from nearby novae involving ONeMg white dwarfs, the detailed examination of ^{26}Al production in novae, and the possible detection of the predicted early gamma ray emission from novae that arises from the decay of the short lived, positron emitting isotopes of CNO elements.

Studies of nova related problems have consumed an increasing fraction of the Principal Investigator's research efforts over the past decade. Current research addresses problems associated with the standard model for the outbursts of the classical novae: the occurrence of thermonuclear runaways (TNR) in the accreted hydrogen-rich envelopes on white dwarfs in close binary systems (see, e.g., the reviews by Truran 1982; and Shara 1989). Research in progress and planned for the next three years has three main objectives: (1) to gain an improved understanding of the early evolution of the light curves of, particularly, the fastest novae; (2) to gain an improved understanding of the relative importance of the various possible mechanisms of envelope hydrogen depletion (e.g. winds, common envelope driven mass loss, and nuclear burning) to the long term evolution of novae in outburst; and (3) to seek to provide a somewhat more definitive statement of the role of classical novae in nucleosynthesis. Our proposed 2-D studies of convection during the early phases of the TNR and our systematic attempt to incorporate an improved treatment of radiation hydrodynamics into the hydrodynamic code utilized in our calculations, are particularly relevant to the first of these objectives. Further 2-D studies of the effects of common envelope evolution are intended to provide more realistic constraints on the mass depletion mechanisms. Finally, detailed calculations of the thermonuclear history of the matter ejected in novae will be carried out for representative nova configurations involving both carbon-oxygen (CO) and oxygen-neon-magnesium (ONeMg) white dwarfs.

Progress in research has been achieved on all these fronts. Researchers who have received some level of support from this grant include Drs. Andreas Burkert (Heidelberg), Ami Glasner (Jerusalem), Wolfgang Hillebrandt (Munich), Hans-Thomas Janka (Munich), Lev Yungelson (Moscow), and Frank X. Timmes (Clemson). Also, Chicago graduate student Yuan Nan Young is currently involved in research concerning critical aspects of convection as they relate to classical nova explosions and concomitant nucleosynthesis. Brief summaries of the results of several research projects are presented below.

Powering the Light Curves of Fast Classical Novae

Observations of fast classical novae indicate the existence of a large and serious disagreement with theory, regarding the maximum luminosities achieved by these systems. Fast novae in our Galaxy, and those in M-31 and the LMC (for which distances are particularly well determined), reach absolute visual magnitudes as bright as -8.5 and can remain brighter than -7 for several days. This behavior has not been successfully reproduced by any self-consistent, time-dependent numerical simulation. It appears difficult to match the observed ~ 3 -5 day period with the intrinsic time scales that characterize the runaway and post-runaway phases of novae. Sound travel time scales and convective time scales are much shorter, and the expansion time scale is only about a day.

The high mass loss associated with (indeed, demanded by) the rise to visual maximum indicates that a substantial fraction of the energy release during the runaway is consumed in lifting matter in the gravitational potential of the white dwarf. To tap this reservoir of gravitational binding energy for powering the super-Eddington photon emission would require the expanded envelope to shrink to a radius of about 10^9 cm again within a few days, incompatible with the observed long-time behavior of the luminosities. The runaway itself is violent and leads to strong heating in the hydrogen layer. However, one has to use very optimistic assumptions about the amount of mass that is heated to high temperatures to explain the super-Eddington phase simply by the cooling of the hydrogen layer on a thermal time scale. Moreover, the convective time

scale is very short and convective energy transport fast, so that the overlying layers are efficiently coupled to the shell burning on top of the white dwarf. Therefore it seems likely that the phase of very high photon fluxes reflects a period of energy generation above the Paczyński value for hydrostatic hydrogen-shell burning. Hayes and Truran (1995) have demonstrated that existing numerical models are energetically capable of powering such observed emission for the requisite timescale, and argue that the discrepancy arises due to the fact that the physics describing the exchange of energy and momentum between the material and radiation has been oversimplified in the hydrodynamical studies published to date. The reason for this failure might be connected with the description of radiative transfer in the current models. While the existence of the super-Eddington peak indicates the importance of non-LTE effects in the mass flow that expands supersonically away from the white dwarf and evolves from optically thick to optically thin conditions, the numerical codes treat the radiation transport by simple LTE diffusion methods. This artificially enforces thermal coupling between radiation and matter out to low temperatures and may well lead to an overestimation of the mass loss rate in the nova wind and a corresponding suppression of the bolometric luminosity. Efforts are currently underway to remedy this situation, by substantial modification of the numerical procedures utilized in our hydrodynamic program (Glasner, Janka, and Truran 1995). A first step will be to replace the LTE diffusion treatment in an elaborate, implicit, hydrodynamical code (Glasner 1995) by a non-LTE flux-limited diffusion method (Janka 1995), employing the Levermore-Pomraning flux-limiter developed for photon transport.

The Nature of the Soft X-Ray Emission from GQ Muscae

Ögelman *et al.* (1993) have recently reported the detection of Nova GQ Muscae 1983 at soft x-ray wavelengths, nine years after outburst, with the ROSAT satellite. The observed spectrum is very soft, and is generally consistent with black body emission from a $\sim M_{\odot}$ white dwarf, burning at a near Eddington luminosity and an effective temperature $\sim 3.4 \times 10^5$ K. Such a soft x-ray signature is entirely consistent with expectations for the long term evolution of classical novae in outburst (MacDonald, Fujimoto, and Truran 1985), as it can arise as a natural consequence of the hardening of the radiation from novae, as the photospheric radius decreases during an extended phase of shell hydrogen burning at approximately constant bolometric luminosity. Truran and Glasner (1995), in a paper recently submitted for publication: (1) review and discuss the observations of Nova GQ Muscae, the prototype event of this nature, (2) present recent calculations which allow us better to understand the timescales for the onset and duration of the observed phase of soft x-ray emission, and (3) address the obvious question as to why it is that GQ Muscae is one of only a few of the recent classical novae to have been found to exhibit this behavior. Truran, Glasner, and Yungelson (1995) have also constructed and evolved models for non-optical, supersoft X-ray outbursts on white dwarfs, while Yungelson, Tutukov, Livio, Truran, and Fedorova (1995) have examined the implications of such outbursts for the observed population of soft X-ray sources in the Galaxy.

Nucleosynthesis in Novae

Classical nova outbursts provide an environment in which hydrogen-burning reactions proceed on carbon, nitrogen, and oxygen (CNO) nuclei, and on heavier nuclei (ONeMgSiS), at high temperatures and densities, on a dynamic timescale. The inclusion of a proper treatment of nuclear energy generation is thus essential to an understanding of the detailed features of classical nova explosions. Nucleosynthesis accompanying these same nuclear burning episodes is also of interest: novae may be important contributors, for example, to the Galactic abundances of the rarer isotopes of the CNO nuclei, ^{15}N and ^{17}O , and to ^7Li , as well as sources of the interesting radioactivities ^{22}Na and ^{26}Al . Confrontation of the expected yields from nova events with observations of abundances in nova ejecta can also serve to impose very important constraints on hydrodynamic models of nova outbursts.

Weiss and Truran (1990) calculated nucleosynthesis accompanying nova outbursts for representative temperature histories extracted from hydrodynamic models, using a greatly expanded nuclear reaction network. Subsequently, this network was incorporated directly into the hydrodynamic code (Politano *et al.* 1995) to permit an exploratory investigation of nucleosynthesis in the ONeMg-enriched envelopes of novae. A discussion of nucleosynthesis in novae based upon calculations available to date is currently being prepared for publication (Timmes & Truran 1995). The potentially important role that abundance constraints can play in guiding theoretical modelling of novae provides the motivation for an ongoing study of nucleosynthesis in novae, which will explore the dependences on the white dwarf mass and envelope composition (Truran,

Glasner, Timmes, & Starrfield 1996). The immediate goal is to provide the details of ‘representative’ models, involving CO and/or ONeMg white dwarfs of masses $\sim 1.0\text{--}1.3 M_{\odot}$, typical of nova systems in outburst (Truran & Livio 1986). We also wish to clarify the dependences of the predicted abundance patterns on the convective history of the envelope matter and the assumed initial composition. Nucleosynthesis calculations supported by this grant have helped to clarify the role of classical novae in the production of interesting radioactivities and of the rarer isotopes of the CNO elements.

Multidimensional Hydrodynamic Studies of Nova Runaways

Spherically symmetric models for accreting white dwarfs that produce thermonuclear runaways (Starrfield et al. 1974, 1985; MacDonald 1980; Nariai, Nomoto, & Sugimoto 1980; Prialnik & Kovetz 1995) show general agreement with the gross features of classical novae explosions, including the total energy output and the typical ejection velocities. They fail, however, in their ability to explain in detail such features as, e.g., the development of the visual light curve, the typical outburst time scales, the non-spherical morphologies of the nebular remnants, and the high concentrations of heavy elements C, O, and Ne detected in nova ejecta, which are sensitive to the consequences of deviations from spherical symmetry. Given the fact that novae are known to be associated with close binary systems, for which a phase of common envelope evolution must accompany at least the earlier stages of the outburst, it is clear that realistic modelling must ultimately involve multidimensional hydrodynamic studies.

A critical feature of the early evolution of the hydrogen shell in response to runaway is convection, which serves to regulate the temperature during the slow stages of the runaway and subsequently to effect mixing of the envelope matter. In all of the 1D models identified above, the temperature at the base of the envelope increases slowly. For temperatures above 2×10^7 K, radiative heat conduction can not transfer the overall energy produced by nuclear reactions, and the base of the envelope becomes unstable to convection. Later, as accretion continues, the burning rate grows until the burning time scale becomes shorter than the dynamical time scale and a TNR takes place. Typically, the rise time of a nova event is of order one day, while the very fast stage of the burning lasts less than an hour. In 1D models, convection acts as a cooling mechanism which regulates the temperature during the slow stages of the burning, but later becomes inefficient.

Since the burning rate is very sensitive to the temperature, very small fluctuations in temperature can lead to large differences between the flash times of different points on the burning shell, much larger than the rise time. A multidimensional analysis is therefore required: The question arises as to whether the initial temperature fluctuations are extremely small, or rather whether there is some mechanism which couples the burning process at different points in the shell. In this regard, Shara (1982) studied thermonuclear powered localized eruptions using semi-analytical models. When neglecting the role that convective motions play in the process, he found that for dense hydrogen envelopes on massive white dwarfs, thermalization time scales can be orders of magnitude longer than thermonuclear runaway time scales, and therefore predicted that localized TNRs are most likely to occur on white dwarfs in the mass range $0.9 < M_{\odot} < 1.2$. Clearly, this analysis should be carefully re-examined, taking into account the effects of convection on the lateral thermalization. Shankar Arnett & Fryxell (1992) and Shankar & Arnett (1994) were the first to carry out 2D calculations of this problem. Being aware of the subsonic nature of the problem and using an explicit hydrodynamic code, with time steps limited by the CFL condition, they restricted their survey only to very strong instantaneous temperature fluctuations that develop rapidly on a dynamical time scale. The initially intensive burning at a point was found to extinguish on a very short time scale, as the perturbed region rises rapidly, expands, and cools.

The aim of our continuing study of this problem is to carry out 2D simulations under more realistic initial conditions. Livne (1993) has developed an implicit hydro code (VULCAN) which enables the simulation of long term subsonic flows. Using the 2D hydrodynamic code recently developed by S.A. Glasner and E. Livne (1995), Glasner, Livne, and Truran are now investigating the role of convection during the early stages of the thermonuclear runaway. Several issues are currently being addressed:

- (1) The long term evolution of the convective flow prior to the runaway and the exact composition structure it imposes by mixing core matter into the envelope, due to the convective overshoot and interactions of the downstream flows with the hard core.
- (2) The exact chemical evolution of the outer layers (with zoning as delicate as our computer resources will enable us).
- (3) The fate of temperature fluctuations in early stages of the runaway.

Two questions are critical to the consideration of gamma ray lines from novae: the magnitude of the dredge-up of matter from the underlying CO or ONeMg core into the hydrogen burning envelope and the time scale for the transport of the radioactive isotopes of CNOF nuclei to the surface by convection, leading to the occurrence of an early gamma ray or hard X-ray burst from novae. Our preliminary studies reveal that convective motions do indeed result in dredge-up of CO rich matter from the core into the hydrogen layers. The extent to which such outward mixing is a general feature of thermonuclear runaways on white dwarfs is now being investigated. We are also studying the details of the convective transport of the radioactive nuclear species to the surface, and the structure of this surface regime, in order to be able to calculate in a more realistic manner the spectrum of the expected early burst of gamma rays and hard X-rays.

Screening of thermonuclear reaction rates and nuclear statistical equilibrium.

While the plasma physics aspects of electron screening have been addressed on an advanced level, applications to problems in nuclear astrophysics often still involve the use of approximations which introduce considerable uncertainties. In particular, prior to our current study, the rate enhancements had been evaluated only for pure capture reactions, (p,γ) and (α,γ) , on the assumption that the radiative width dominates. We note that reactions involving charged particles in both incoming and outgoing channels play an important role in many astrophysical environments where ignition occurs under degenerate conditions. Those include $^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$, $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$, and many (α,p) reactions in Type Ia supernova events, (p,α) reactions associated with the hot CNO cycles in novae, and (α,p) reactions during combined hydrogen and helium burning in X-ray bursts on neutron stars. Hix, Thielemann, & Truran (1995) have derived general expressions for the screening enhancement factors for this type of reaction. In addition, a more general expression is derived for particle capture and photodisintegration reactions, which does not rely on the implicit assumption that the incoming channel is not the dominant one. We also show how nuclear statistical equilibrium (NSE) is affected by the screening of reaction rates, and demonstrate that the effects of detailed balance only partially compensates for the screening enhancement. The remaining correction factor results in an abundance enhancement proportional to $\exp(\Delta B/kT)$, where ΔB is identical to the enhancement of the binding energy of the nucleus in a Coulomb lattice. As Coulomb screening plays an important role in NSE abundances, we provide specific examples and illustrate the typical patterns to be expected for the modified abundances.

PUBLICATIONS RESULTING FROM NASA/GRO AWARD

PUBLICATIONS OF THE PRINCIPAL INVESTIGATOR SUPPORTED IN FULL OR IN PART BY NASA GRANT NAG 5-2081 AT THE UNIVERSITY OF CHICAGO, 1993-95

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